Definition and construction of noise budget in atom interferometry

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There are several classes of atom interferometers and, despite the similarity of the high-precision measurements they enable, the operating principles underlying the coupling of these detectors with the perturbation of interest are different. In general, the physical mechanism that makes the interesting effect manifest is also responsible for the sensitivity of the system to a variety of disturbances. When these perturb the ideal working point of the interferometer and modify its response, additional terms due to artifacts and fluctuations appear in the phase of the detector itself. For they are characteristic of the actual realization of the interferometer, the dominating noise sources depend on the specific class of instrument we consider. We focus on interferometers based on the interference of atomic internal states. In this class of detector, transitions are induced between two atomic states and the perfection of such manipulation is extremely sensitive to the motion of the atom with respect to the electromagnetic field that induces the transition. More specifically, since the ideal working point identifies the resonant condition of the atomic transition as matched by the excitation frequency, any deviation from it generates a phase. When time-resolved, this informs us of the dynamics ot the two atomic states and is the result of a variation in their relative evolution, that is not matched by the *resonant* excitation field.

There are three points worth noting that summarize the action of the main noise sources in this interferometer:

- changes of the phase of the excitation field, when they induce a deviation from the resonant condition, have the same impact as changes in the evolution of the two resonant states;
- once they are launched, atoms are a free falling isolated object that only interacts with the gravitational field and collisions can only occur within the beam, depending on the thermal distribution of the collection of atoms when they access the vacuum tube;
- different noise sources compete with the signal of interest; the amplitude of the extra terms they generate depends on their transfer function, and this in turn depends on the configuration of the detector. This implies that white noise sources generate fluctuations of the output signal, whose power spectral density is frequency dependent. As for the response to the physical perturbation we want to investigate, it should optimally preserve the signal of interest and be fully characterized (for extraction purposes).

We consider the limited sensitivity due to the dominating noise sources of this class of atom interferometers. Those are compared to the impact of different disturbances that are relevant in another demonstrated approach: that is matter-wave interferometers consisting of slits and diffraction gratings. These split and reflect particle beams, whose propagation is determined by their De Broglie wavelength. Since in this class of interferometers there is a contact interaction of the matter-waves with the optics, any motion or distortion of the reflecting surface results in an altered propagation of the deflected beam; this is the reason of the similarity of seismic and thermal noise in matter-wave and laser-light interferometers. A generally distinguishing feature of this class is that they are rigid. This has significant implications in the derivation of the interferometer phase.

We present the fundamentals of our mathematical analysis, which accounts for the different operating principles underlying the two types of atom interferometers. That is instrumental in understanding their sensitivity. The noise budget curves we construct are the result of such analysis and are determined by the response of the instrument to the scientifically interesting signal and to noise sources.

They thereby suggest the leading actions towards the design and construction of an effective interferometer, by

1. providing the prioritization of the disturbances to be kept under control. Their relevance can be reduced by direct attenuation of the source or by design (mastering the transfer functions);
2. enabling the exploration of the domain of feasible parameters, in order to identify an "optimal" set.

We illustrate these investigations through applications to the state-of-the-art technology in atom interferometry. More specifically, we discuss the challenging requirements that high-sensitivity time-resolved detection bring forth, along with the wealth of general relativity effects that could be directly probed by the next generation of interferometers.